VII Novel Generation

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VII.1 Development and Testing of a Rotating Supersonic Shock Compressor

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Objectives

- Demonstrate a high pressure ratio supersonic shock compression rotor (Rampressor^{TM}) to expand on the low pressure ratio success and show feasibility of high-efficiency shock compression technology for stationary devices

Approach

- Use analysis tools validated by the low pressure ratio testing to design a high pressure ratio aerodynamic flow path
- Design, manufacture and test a laboratory rig that will facilitate the understanding of the aerodynamic features of the high pressure ratio shock compression rotor
- Analyze the performance data from the compression rig test to anchor our analysis tools at high Mach number ~2.6
- Evaluate the technical potential of the novel compression technique

Accomplishments

- The lower pressure ratio supersonic shock compression rotor demonstrated several important milestones
- Shock structures were established in all of the supersonic shock inlets on the rotor (3 inlets per rotor)
- The rig operated near design pressure ratio (~2.2:1) and mass flow (~1.8 lbm/sec)
- The rig achieved ~75% rotor efficiency without the optimization of the geometry, bleeds, tip clearance, etc.
- The technical design and analysis tools have been validated for Mach 1.6 designs
- The design effort on the high pressure ratio compressor has yielded the following results:
- Improved computational fluid dynamics (CFD) analysis tools and techniques
- Enhanced performance modeling and prediction tool
- Designed superior tip clearance control system
- Identified and addressed the mechanical structure and system challenges of high compression ratios over a single-stage device, e.g., rotordynamics, bearing life, high rotational stresses, high secondary flow temperatures

Future Directions

- Design the second Rampressor test rig to run at higher pressure ratio and higher mass flow (1500 cfm)

- Achieve higher efficiency through optimization of the tip clearance and rotor geometry
- Investigate key technology challenges to successfully incorporate the superior compression technology into a commercially viable compressor product
  - Aerodynamic optimization
  - Tip leakage mitigation
  - Rotor mechanical design optimization
  - Diffusion pressure loss mitigation
  - Thrust load mitigation
- Apply the technical knowledge gained to compression of high volumes of CO_2 in support of Clean Coal, FutureGen and Carbon Capture & Storage programs

Introduction

Since the sound barrier was broken in the late 1940s, ramjet engines have been widely used as a means to propel aerospace vehicles at supersonic speeds. The underlying supersonic aerodynamic shock theory and technology is very well understood and fully characterized. Ramgen Power Systems' ("Ramgen") primary innovation has been to apply ramjet engine concepts in a stationary "shock" compressor. The principal advantage of shock compression is that it can achieve exceptionally high compression efficiency at very high compression ratios.

The importance of a breakthrough compression technology cannot be overstated. The air and gas compression industry is often referred to as the Fourth Utility. Compressed air is one of the most important utility requirements of industrial manufacturing. Air compression is also a critical element in determining the efficiency of all types of combustion engines, including gas turbines, internal combustion engines and hybrid fuel cells. Gas compression is the key to the efficient compression of CO_2, which is increasingly seen as pivotal to the clean generation of power from coal.

Approach

The technology development path for the Rampressor technology started with our rotor test rig at relatively low pressure ratio and performance. The next step is to design a higher pressure ratio and performance rotor test rig - the 2nd Rampressor Test Rig. This test will anchor our design and analysis tools at high pressure conditions. Successful rotor test results will allow us to design a compressor package at any commercially desirable pressure ratio and flow requirement. The bridge between successful rotor testing and a compressor package demonstration will be crossed by investigating the design requirements and options for an industrial drive, rotor manufacturing, controls, tip clearance system, self-contained supporting systems, etc. The next test rig (Alpha rig) will be a CO_2 compressor demonstrator including all the major components of a functional compressor package (drive, supporting systems, controls, etc.). Following the Alpha rig, there are four Beta pre-production test units planned to complete the development of the compressor.

Results

During FY 2004, Ramgen succeeded in completing testing of the first Rampressor compressor test rig; see Figure 1. Testing was run at the Boeing Nozzle Test Facility in Seattle, Washington. The test was successful in many ways.

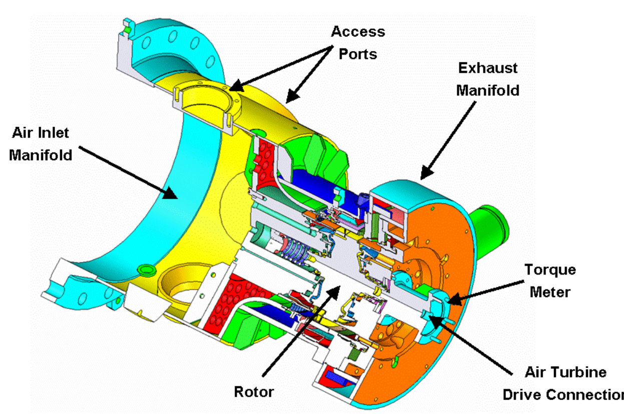

Figure 1. Test Rig

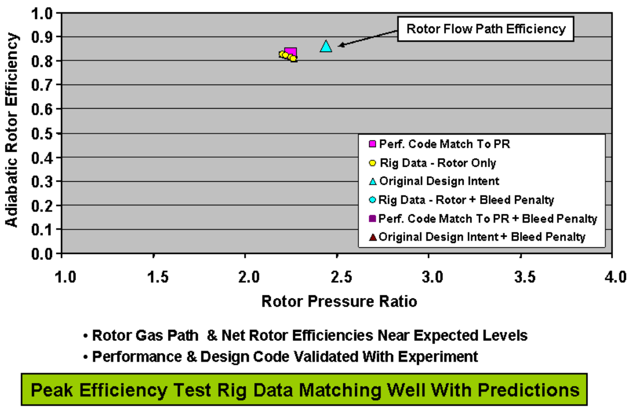

Figure 2. Rampressor Efficiency vs. Pressure Ratio

One of the testing accomplishments achieved by Ramgen was to successfully establish a shock structure within the inlet that permits compression of the air by supersonic compression waves – the inlet has been "started". Inlet "starting" is a significant milestone in any supersonic inlet test program, whether it is for supersonic air breathing missiles or aircraft (high-speed military jet fighters, SR-71, or the Concord). Inlet starting is defined as stable supersonic flow throughout the converging/ contracting portion of the inlet geometry. The minimum flow area of a fixed geometry inlet is sized for the design operating Mach number. As the inlet velocity (rotor tip speed) approaches Mach 1 (speed of sound), a fixed geometry inlet cannot swallow all of the air approaching the inlet. As a result, a normal shock wave is formed in front of and diverts flow away from the inlet. This normal shock wave results in subsonic flow into the inlet, an "unstarted" condition, which is not an efficient operating condition for an inlet designed for supersonic flow.

During the test, many different test conditions were run, from low pressure ratio/low mass flow to higher pressure ratios/mass flows. These collected data points form the basis for a preliminary compressor map. A key conclusion from our testing was that our performance prediction tools replicated the experimental results. The measured rotor efficiency, pressure ratio, rotor exhaust Mach number and flow angle all closely aligned with the predictions from the analysis tools; see Figure 2. In addition, our compressor mapping showed that the Rampressor rotor does not exhibit any violent surge (or failure to hold pressure ratio) characteristics. In

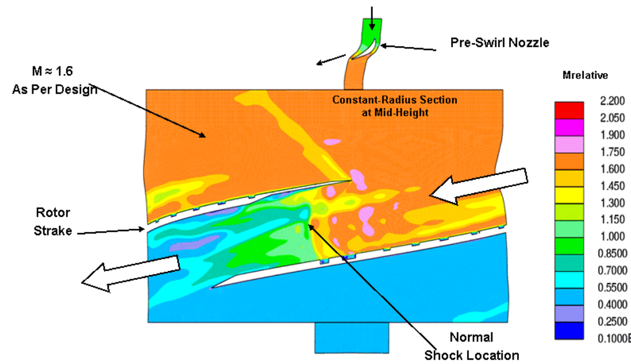

Figure 3. Sample CFD Run of Rampressor Flow Path

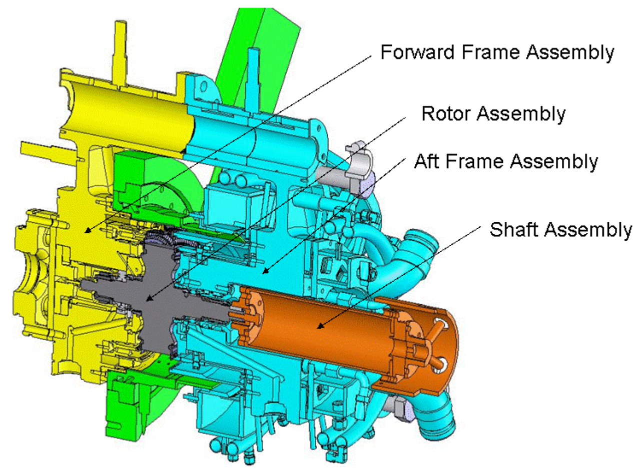

Figure 4. Next Generation Test Rig

fact, the surge characteristics were quite benign and reversible without having to go to great lengths to re-start the inlets.

After the testing was concluded, the test data was used to anchor or calibrate our CFD models. Full flow path 3-dimensional viscous modeling was used; see Figure 3. Once we established that CFD could duplicate the test conditions and results, we used the CFD tool to start designing the next generation test rig for high pressure ratio; see Figure 4.

Conclusions

Ramgen Power Systems Inc. has completed a series of tests that validates the technological base for a compressor product and for a small gas turbine (800 kW to 5 MW) to generate electricity. Past compressor tests have successfully demonstrated a number of the fundamental technical requirements that are critical to achieving high-efficiency supersonic inlet compression as required for industrial gas compression and engine applications, like fuel cell hybrids. Ramgen will continue to validate the engineering design tools needed to move towards a successful product. These products will leapfrog current technology in terms of higher efficiency, lower cost and lower emissions.

Special Recognitions & Awards/Patents Issued

1. Provisional Patent application submitted for Fuel Fired Compressor and Method of Use in Oxygen; Ramgen Case Number RPS-3150; October 7, 2004

FY 2005 Publications/Presentations

1. Paper for IMECE 2004 on Supersonic Compression Stage Design & Test Results; dated November 14, 2004
2. Paper for ASME 2005 Conference on Conceptual Design of a Supersonic CO_2 Compressor; ASME 2005 Document GT2005-68349, dated June 6, 2005
3. Paper for ASME 2005 Turbo Expo on Insertion of Shock Wave Compression Technology into Micro Turbines for Increased Efficiency and Reduced Costs; dated June 6, 2005
4. Paper for ASNE 2005 Symposium on Critical Enabling Technologies for Long-Endurance Unmanned Surface Vehicles; dated July 19, 2005